

Shell House Evaluation

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1.0 Introduction

The scope of work first required research on Poly Canyon's Stress Reversal: Pre-Tension Post Compression Concrete Shell^A. The concrete shell focused on the funicular shape to induce pure compression when the gunite was applied to the pre-tension cables. The shell structure was originally built in 1964 and an interior addition was added in 1976. The structure was dubbed Shell House. The original project reports were found on microfilm in the archives of Kennedy Library. No such building plans or sections were found, and the issue became finding a means for properly modeling the geometry. Several methods were considered, but the 123D Catch program by Autodesk was selected because it offered the best means of accurately the double-curvature of the structure. The intent of the research was to understand the performance of Cal Poly's historic structure in a large seismic event.



^B Photo from the Tribune c. 1980

2.0 Summary of Preliminary Research

The original project was built by six Architecture and Architectural Engineering students in 1964 and was named Stress Reversal: A Pre-Tension Post Compression Concrete Shell^A. The structure was built along the North side of Brizzolara Creek in the heart of the Poly Canyon Experimental Structures Laboratory. The project advisors were Wesley Ward and Harvey E. Koehnen

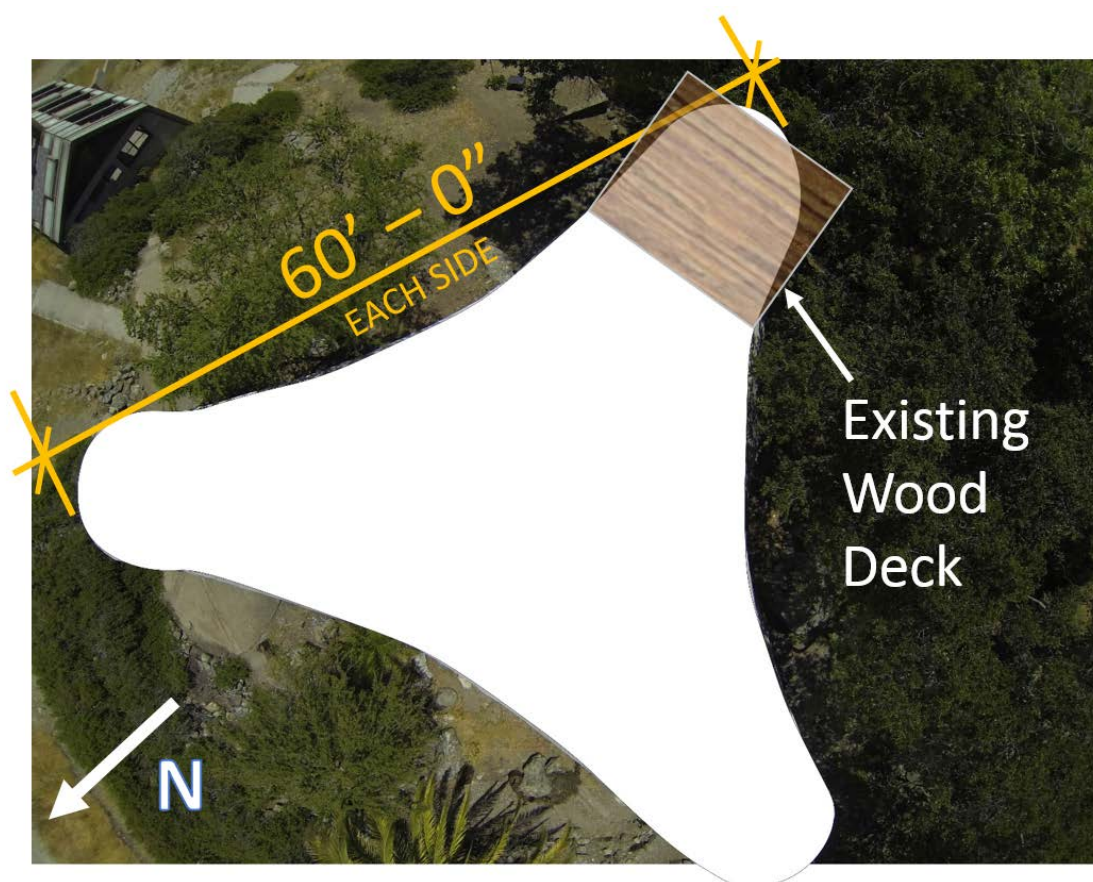
The concrete shell focused on the funicular shape to induce pure compression when the 5000 psi gunite^A was applied to the pre-tension cables. The structure has three cantilevered corners allowing wide panoramic views and entry, and makes contact with the subgrade foundations in between each of the cantilevers at two closely spaced locations. From observation, the shell appears to be the thickest at the connection points, ranging from 14" to 18" thick and 28" to 36" wide. Each of the three cantilevers sections reaches a peak height at least seven feet from the top of slab-on-grade. The shell thickness varies tremendously, getting as thin as 6" in some regions and reaches 9-1/2" around the perimeter. Away from the edge of the shell the actual thickness is unknown and accurate means of verifying would require intrusive coring samples on the structure.

The original construction started with a temporary support column installed at the center of the structure. The column supported a ring that draped cables down to eyebolts at the footing connections. The footing also featured a tension ring. The perimeter cantilever also had longitudinal cables connecting to the center ring at the top. Main catenary cables are 5/8" diameter low carbon steel cables but additional 5/16" and 1/2" cables were added for additional continuity and strength^A. Turnbuckles were used to tension the cables and symmetric tensioning was a "delicate balance"^A. Nearby trees were used for stability and reference points but additional temporary supports were also required.

Students from the original project emphasized the need for symmetric placement of the gunite to maintain balance in the structure. A 1/4" metal mesh

(20 gage "Expand X metal lath by US gypsum) was tied into the tensioned cable system. The intent was to give an adequate surface to apply the gunite but the mesh also added continuity and additional strength. The process continues until the cables are completely covered in gunite. The shell was disconnected from the central column when the shell in compression was stable.

KEY PLAN



3.0 Initial Modeling Considerations

Although 123D Catch was used for modeling other considerations included various surveying techniques. Manual surveying, as taught in the Surveying classes offered at Cal Poly, would be incredibly tedious and possibly dangerous. It would be nearly impossible to develop an accurate model from taking relative distances and angles. Additionally, the structures peak is nearly vertical and climbing would require ropes and significant rock climbing experience. Contracting a professional surveying company was the next option, but no local places offered the services needed to get the model directly into a structural program. Ideally the double-curvature would follow a funicular shape, putting the shell into pure compression under gravity loading. Reverse engineering this funicular shape was another consideration but there was not substantial evidence the actual shape matched the theoretical shape.

4.0 Modeling Procedure

The 123D Catch program uses digital photographs to create a computer model. For a successful model, pictures must be taken 360 degrees around the object and at various elevations. Pictures must lap over one another in order to prevent timely run times and error messages. 123D Catch is quite intuitive but does take some practice to get a good model. The challenge is picking the right pictures. The tutorial recommends around 35 pictures but can process up to 70. This limit poses a big challenge because there is a lot to capture, and too much lap coverage becomes an issue. Blurry pictures can also throw off the model and reflective surfaces can be entirely left out, modeled as holes. The concrete shell was an ideal texture for this program because of its color and lack of shine.

Originally over 500 photographs of the exterior and interior of the Shell House were taken and the 123D Catch model was unable to be created. The exterior provided a front corner of one of the cantilevers, but due to the natural topography, only one side of the structure could be captured. This model was far insufficient for structural modeling. The interior portion did not render any models because of the lighting and unusual geometry. Portions of the interior are coated with plaster and the reflective surface is also a likely cause for failure to create a model.

After numerous failed attempts a drone was used to capture aerial photos via Go-Pro. The drone allowed for better photo quality at all locations and elevations. Over 500 additional pictures and videos were taken and appropriate pictures were selected to get a decent model. The model covered over 90% of the area, only leaving out a portion of a cantilevered region at the South end of the structure. The nearby trees distorted this region of the model and it ultimately can be identified by the squared off section in the final RISA-3D model. The model showed a majority of the structure clearly and supports could be identified to the ground connection.

The program layers the photos on top of the wire mesh model showing a realistic rendering or a wire frame view. Regions of the model that are captured but were not essential to the structure, such as nearby dirt and trees, were removed. The initial model was proportionate but 123D Catch modeling does not have assumed units. However, the program does allow for inputting reference distances taken from field measurements and scaled the model based on these input dimensions.

At this point there was a computer model, but a program suitable for structural analysis was required. Both CSI programs, ETABS and SAP, were not compatible with any of the exported files from 123D Catch. The same went for a RISA-3D and an intermediate program became essential. The wire mesh would not register as a surface, therefore the 123D Catch model was imported into Rhino. In Rhino the wire mesh needed to be reduced to allow for the "MeshtoNURBS" tool to work. The initial complexity of the mesh was ten times more than the tool could process, and therefore the mesh had to be reduced by this amount. The surface still clearly kept the original shape, reducing the line work but maintaining the intricacies of the curvature. The model was finally ready to be input into a structural program.

For an unknown reason the CSI programs could not register a compatible format from Rhino. The Rhino model did however import into RISA-3D, creating a system of members without material properties. The members formed the surface and typically were triangular. After checking the scale and creating material properties for the 5 ksi concrete, each plate element was individually drawn in by connecting the corners of the surface. This was done using hundreds of flat plates typically with an 8" thickness. Originally they were modeled with 6" thickness but this seemed to possibly lead to an under-conservative seismic weight. To increase the base shear the shell was thickened to a reasonable approximation for perimeter thickness. As previously stated in this report, the shell thickness away from the perimeter is entirely unknown.

Connections were modeled by placing two pinned support conditions about six feet on each of the three sides. Analysis for these connections to the foundation was impossible without knowing the original member sizes of the steel or foundation. The plates most adjacent to the ground were increased to 15 inches to try to add stiffness that more accurately represents the actual structure. Following this procedure there are regions in the models that at particular views appear to articulate away from the desired curve. These articulations do not seem to change the analysis because of their mild nature, but this is the largest flaw in modeling the system with plate elements. See section 7.0 for ideas for future projects and suggestions for improving the modeling procedure.

The cracked section properties of the shell were assumed to parallel that of a column rather than beam element. The ACI allows for 30% of the gross moment of inertia for beams, but an increase to 70% for columns because of the aid of the compressive forces. The weight of the structure in the catenary shape ideally creates pure compressing. This is a hard task to achieve at full scale, but the compression can still be assumed to help reduce the size of cracks induced moments from gravity or seismic loading. To model the effective stiffness of the cracked section, the modulus of elasticity was reduced to 70% the theoretical value.

The analysis conducted was limited to static-elastic, which allowed for neglecting the steel in the shell for simplicity purposes. The model was analyzed separately for gravity and seismic loading at first to see if the results seem plausible. Large seismic events were modeled in each direction.

5.0 Results

The results from the RISA-3D model indicate that the structure is adequate in bending, compression, and shear. As expected, the gravity load case indicated the catenary shape was modeled, as seen in the normal force graphic below in Figure 1.

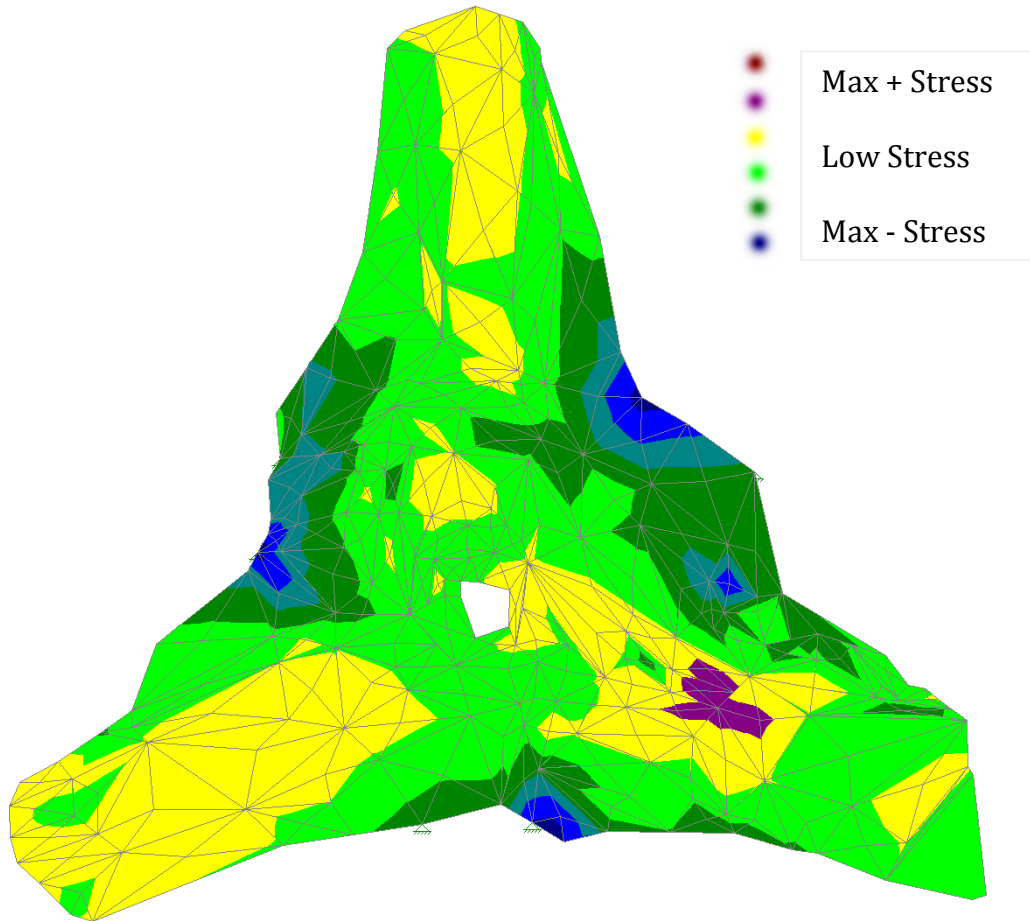


Figure 1 Normal Stress Plot under Gravity Loading Plan View

Nearly all of the structure is in compression and only small regions of the shell are in tension. This matches the predicted shape by the design engineers. Large amounts of compression are seen near the supports, which is also consistent with assumptions.

The catenary shape is ideally under pure compression, thus having minimal internal moments. The internal moment is plotted in Figure 2 below.

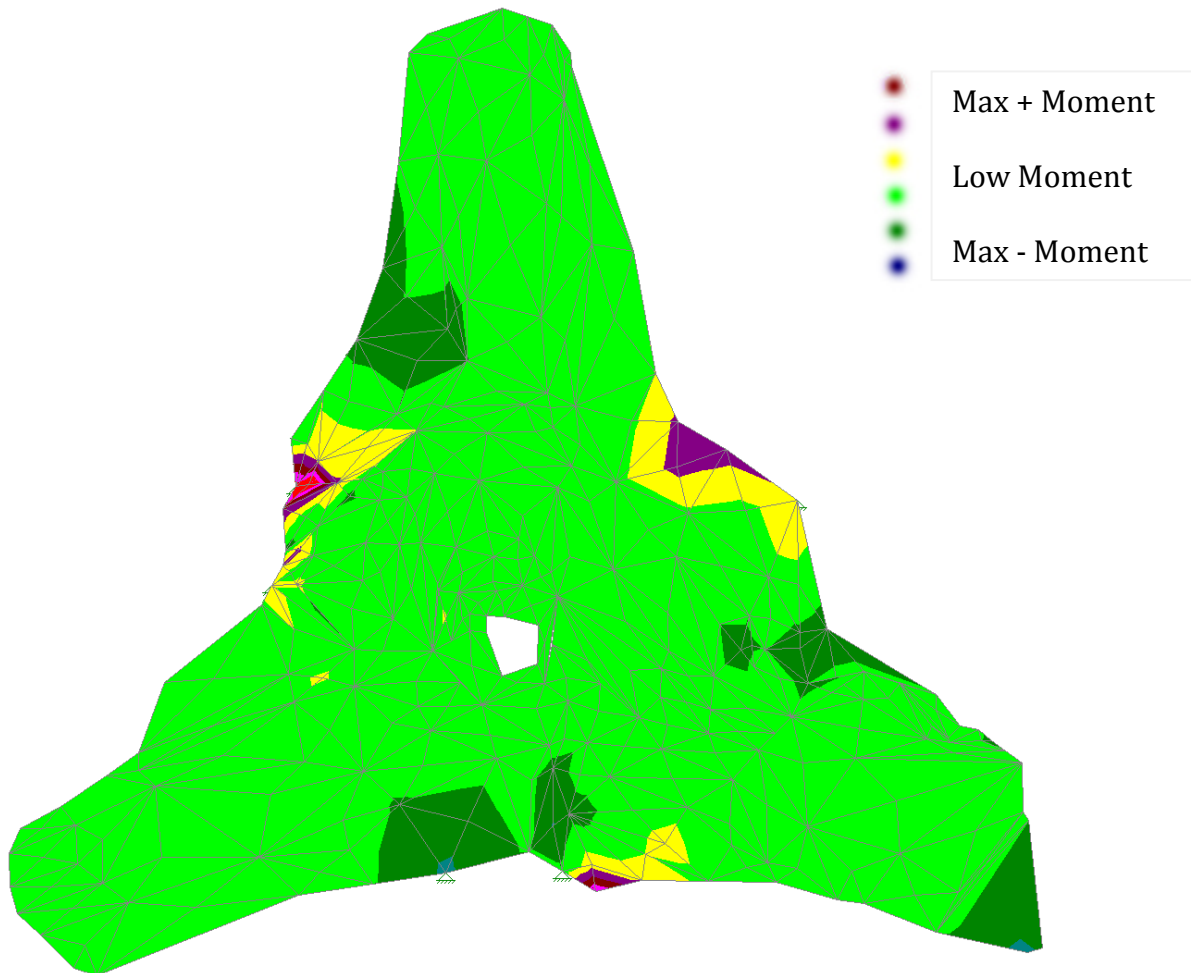


Figure 2 Bending Moment Plot Under Gravity Loading Plan View

The plot shows there are locations that have a moment, however, most of these are relatively small and are not a major concern.

The shear demand under gravity loading was considered as a baseline to compare with the seismic loading. The shear is plotted in Figure 3 below.

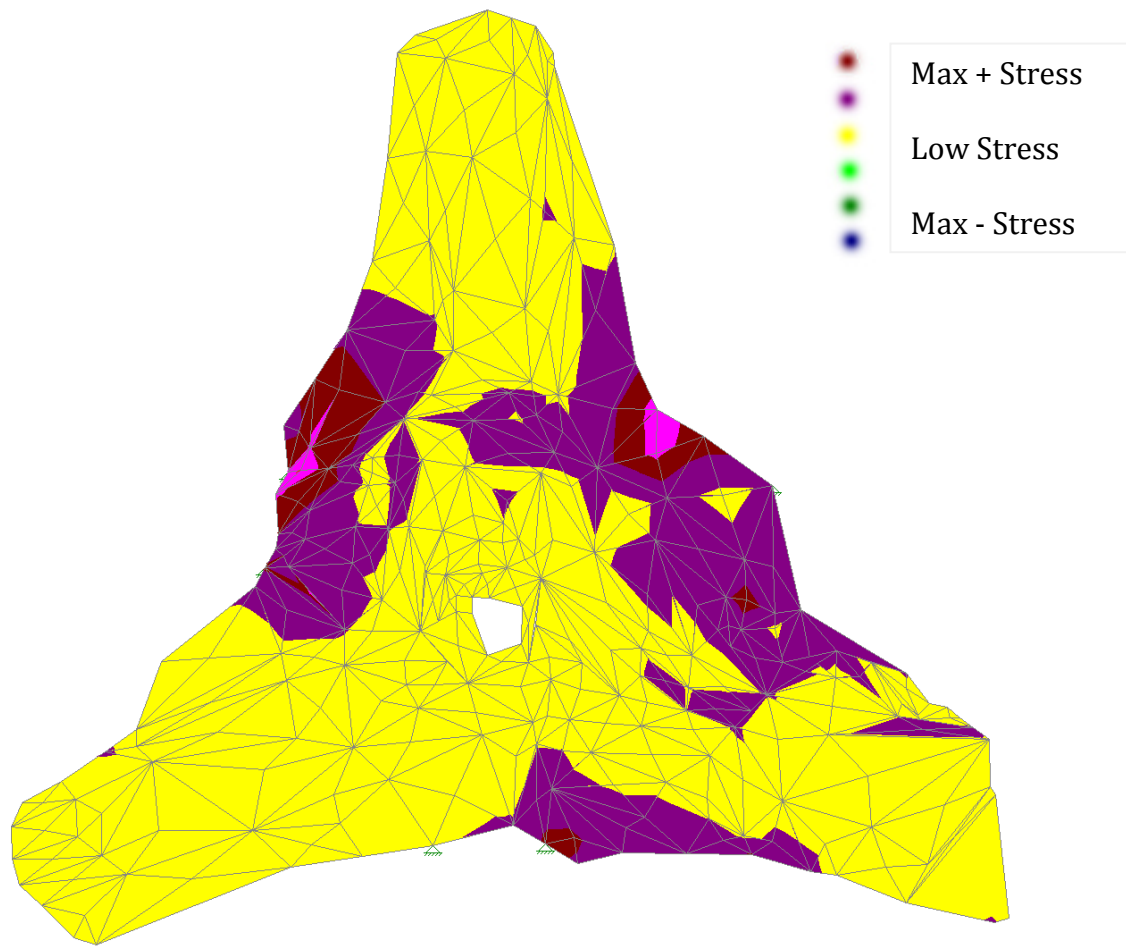


Figure 3 Shear Stress Under Gravity Loading Plan View

The plot shows locations of high shear stress. Shear is a concern because it is a brittle failure. The shear plot for gravity is used to compare to the seismic loading shear plot, seen in Figure 6.

The purely seismic load case indicated slightly more areas of high normal stress, as seen in the normal force graphic below in Figure 4.

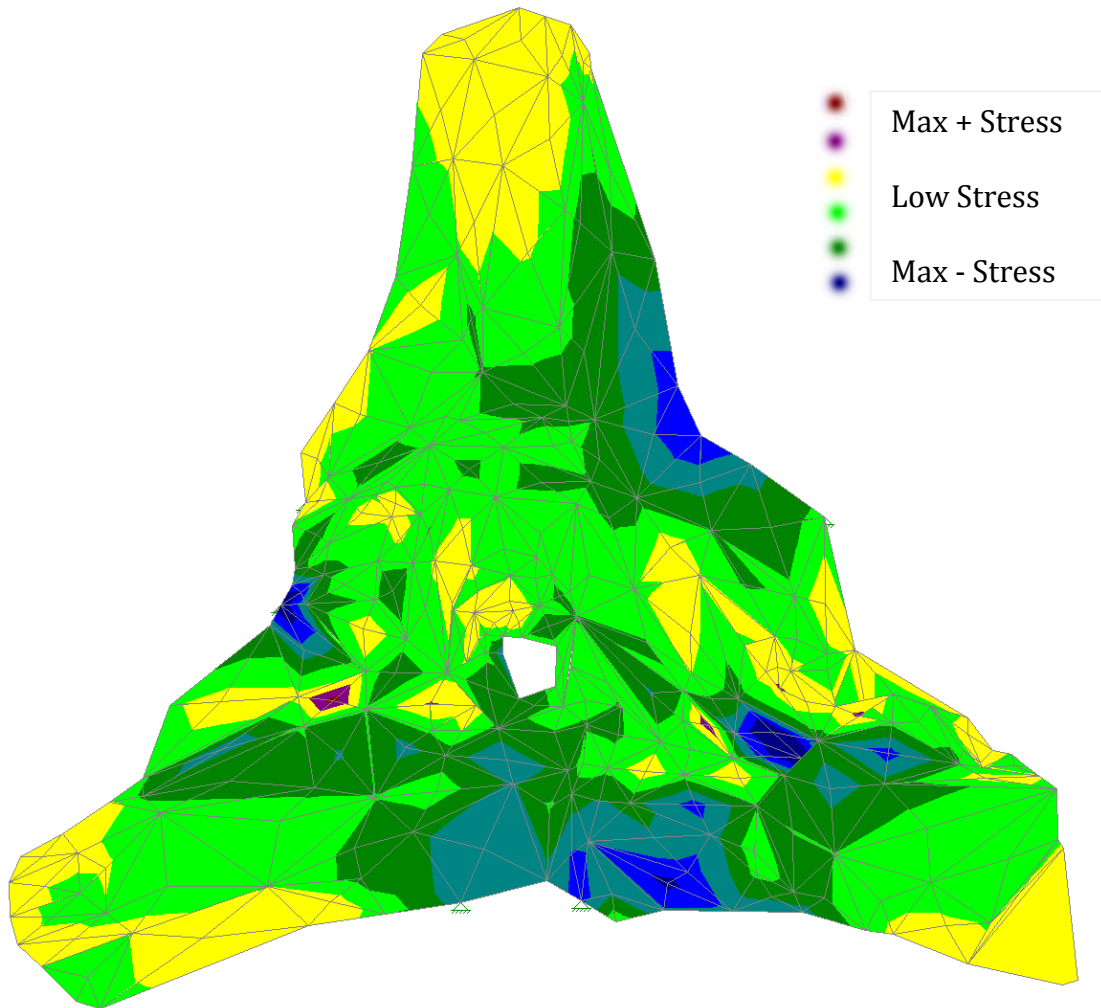


Figure 4 Normal Stress Plot under Seismic Loading Plan View

The increase in normal stress has been exaggerated by applying a conservative seismic event. Even with this large horizontal force, the structure seems to be adequate.

The catenary shape is ideally under pure compression, thus having minimal internal moments. The internal moment is induced though in several locations when seismic loading is applied as seen in Figure 5 below.

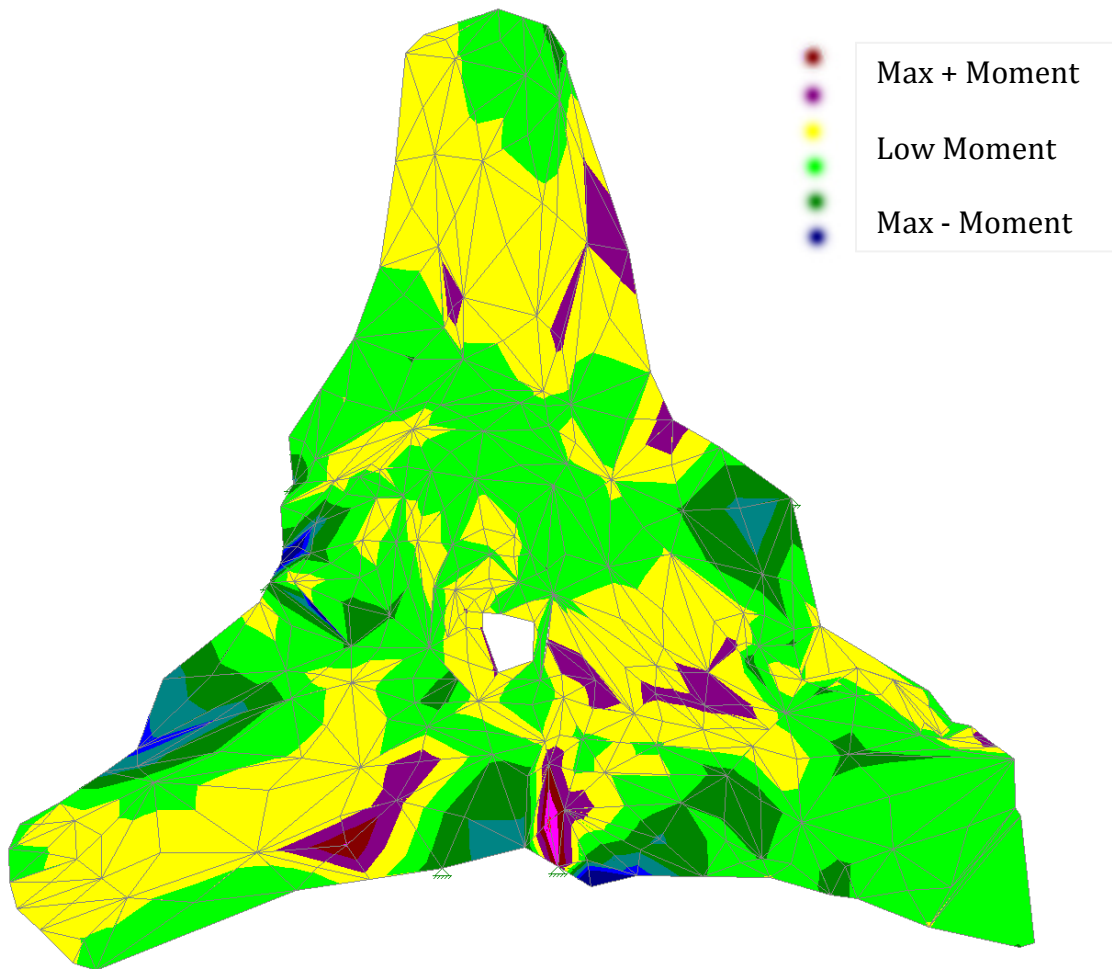


Figure 5 Bending Moment Plot Under Seismic Loading Plan View
The plot shows there are several locations that have a moment, however, although these moments are increased from gravity, the structure still remains stable.

The shear demand under seismic loading was compared to the baseline gravity plot in Figure 3. The shear under seismic loading is plotted in Figure 6 below.

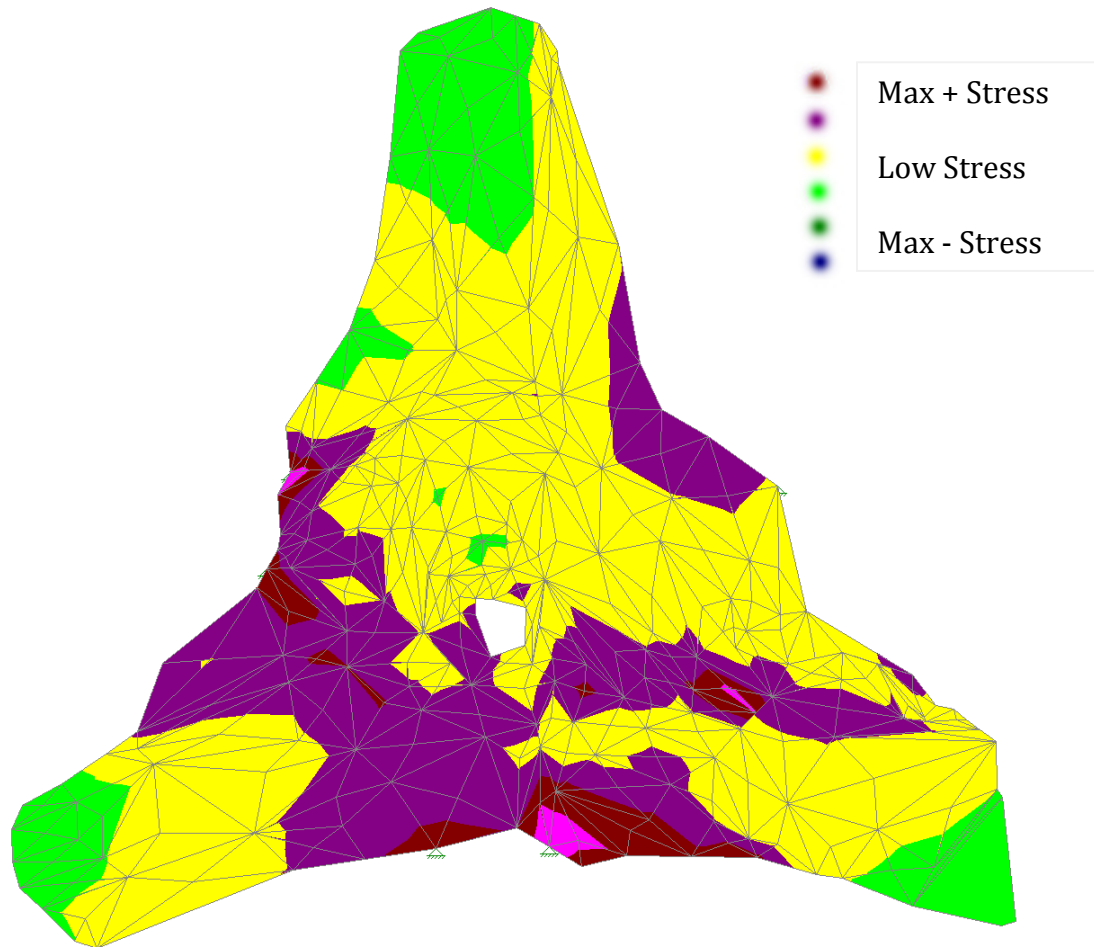


Figure 6 Shear Stress Under Seismic Loading Plan View

The plot shows locations of higher shear stress. Shear failure is a concern because it is a brittle failure. The shell currently lacks shear cracks with large openings, therefore without shear stresses being scaled several times the gravity loading, it can be concluded the shell has enough continuity to prevent a collapse even if a large seismic event damaged a region. The steel reinforcement and metal lath certainly add enough capacity.

Brief hand calculations have been included in the Appendix to try to verify RISA-3D results. These hand calculations are quick checks and assume a simply supported beam that is a one-foot strip. Basic loads were applied and the informal nature of the hand calculations only gives ballpark values. The numbers do not correspond well with RISA-3D for this reason, but this was enough to conclude the structure is adequate.

The connection to the footings featured eyebolts and welded gusset connections but the size of the members was not found and further analysis could not be conducted. These connections are where load concentrates and this leads to a concern listed in Section 6.0.

6.0 Concerns

The final conclusion from this report is that the shell structure is adequate under gravity and seismic loading. This project does not report on the connections to the foundation and this the main concern. Proper waterproofing at the connection from the shell to foundation cannot be guaranteed. This raises the concern for potential corrosion of the steel at the anchor connection.

The other major concern is the actual thickness of the shell. Although measurements could be taken around the perimeter, it is impossible to figure out the thickness near the center ring at the top. This could lead to a severely under-conservative estimation for the weight of the structure. For this reason, the model was changed from 6" to 8" thick, adding 33% to the base shear. Ideally there would be a better way to accurately model the thickness but because it is adequate by so much as is, this concern may be overlooked.

The shell model also shows minor undulations or imperfections in the shells model. Somewhere in the modeling procedure these undulations arose. They are not a major concern however because even with these the structure was adequate.

7.0 Ideas future projects/Suggestions

The projects scope of work could not cover every possible form of analysis. The project required much of the initial research to be conducted before the model could be built. The model was not successful at loading into ETABS or SAP, which would offer more advanced modeling options.

It would be a full project in itself to analyze the steel in the structure. The steel is pre-tension, but this was neglected throughout this project for simplicity. The design tension levels and actual tension levels of the cables were not recorded in the research discovered. Thus shortage of information makes pre-tension analysis a very difficult challenge that might not be worth the headache.

Project advisor and Associate Dean, Kevin Dong, suggested a method for better understanding the thickness of the interior portion of the shell. By taking photographs of one of the supports, including interior and exterior photos, the interior and exterior surfaces may be modeled. Therefor, the space between the two surfaces would indicate the thickness after proper scaling is done to the model. This may be more successful with two separate 123D Catch models and a series of reference points. Although this is more challenging on model coordination, the first method may not be able to yield a model because of the complexity and lighting.

8.0 Appendix

Citations

- A Stress Reversal: Pre-Tension Post Compression, 1964
Kennedy Library Senior Projects Microfilm
Members: Larry D Gangswisch, Ronald W. James, Raymond W. Ketzell,
 Roger R. Marshall, David A. Wright, & James J. Zimmerman
Advisors: Wesley Ward & Harvey E. Koehnen
- B Poly Canyon's Shell House turns 50 years old, The Tribune c. 1980,
Middlecamp, David
- <http://www.sanluisobispo.com/news/local/news-columns-blogs/photos-from-the-vault/article39468666.html>

ACI 318-14

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Larry D Gangswisch
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James J. Zimmerman

and:
Advisors, Wesley Ward
& Harvey E. Koehnen

For the time invested in designing a bold structure that has passed the test of time for over 50 years with great success. You have inspired many young minds to challenge themselves beyond what they thought was possible.

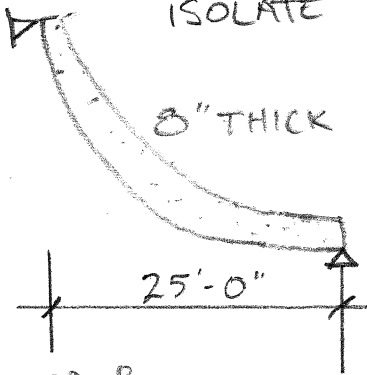
To Project Advisor and Associate Dean Kevin Dong for the feedback and helpful advice for the challenges of this project.

To Dave Kempken, for the advice to look into the 123D Catch program, which led to the successful digital model.

And to Jesse Vestermark, for all of the help finding the research documents and for the help learning the microfilm machine at the library.

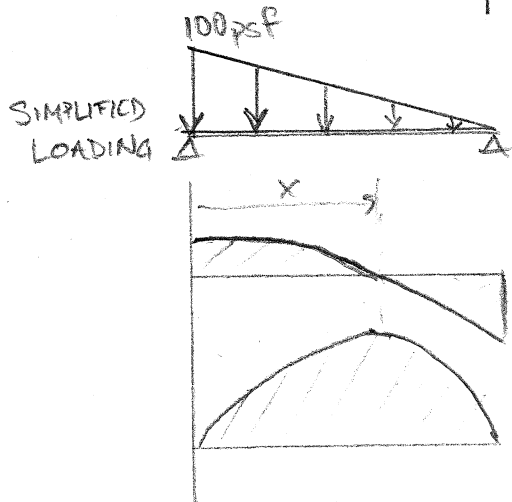
BENDING STRESS CHECK

ISOLATE 1' WIDE STRIP



FOR SIMPLICITY, ISOLATE DEAD LOAD

$$w = \frac{8"}{12 \frac{in}{ft}} (145 \text{ pcf}) \approx 100 \text{ psf}$$



$$R_1 = \frac{2wl}{6} = 833 \#$$

$$R_2 = \frac{wl}{6} = 416 \#$$

$$V_1 = 833 \# \quad x = (1 - 0.5774) 25' = 10.5'$$

$$V_2 = 416 \#$$

$$M_{MAX} = \frac{2wlx}{9\sqrt{3}} = 0.1283wl\theta = \underline{4.0 \text{ k-ft}}$$

CAPACITY

$$a = \frac{A_s f_y}{0.85 f'_c b}$$

$$a = \frac{0.5(50)}{0.85(5)(12)} = 0.5"$$

SINCE ACTUAL STEEL SPACING IS UNKNOWN, ASSUME 1/2" CAGE @ 6" O.C.

$$A_s = 0.5 in^2 / ft$$

$$f_y = 50 \text{ ksi}$$

THIS ALSO ACCOUNTS FOR 1/4" MESH

$$M = A_s f_y \left(d - \frac{a}{2} \right) = 0.5 in^2 (50) \left(4" - \frac{0.5}{2} \right) = \underline{94 \text{ k-ft}} > 4.0 \text{ k-ft}$$

OKAYSHEAR

$$V_c = 2\sqrt{f'_c} bd = 2\sqrt{5000} (12" \times 4") = 6,800 \# \quad \underline{\text{OKAY}}$$